MEASUREMENTS OF WIND VECTORS, EDDY MOMENTUM TRANSPORTS, AND ENERGY CONVERSIONS IN JUPITER'S ATMOSPHERE FROM VOYAGER 1 IMAGES

Reta F. Beebe[1], Andrew P. Ingersoll[2], Garry E. Hunt[3], Jim L. Mitchell[4], Jan-Peter Müller[3]

[1]Department of Astronomy, New Mexico State University, Las Cruces, New Mexico 88003

[2]Division of Geological and Planetary Science, California Institute of Technology, Pasadena, Calif. 91125

[3]Laboratory for Planetary Atmospheres, Department of Physics and Astronomy, University College, London, London WC1E 6BT, England

[4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif. 91125

Abstract. Voyager 1 narrow-angle images were used to obtain displacements of features down to 100-200 km in size over intervals of ten hours on February 26-27, 1979. A global map of velocity vectors and longitudinally-averaged zonal wind $\bar{u}$ as functions of latitude are presented. Denoting departures of the zonal and meridional wind from their longitudinal means by u' and v', respectively, the velocity correlation $\overline{u'v'}$ and the meridional gradient $d\bar{u}/dy$ are compared as functions of latitude. A weak but statistically significant positive correlation is found. The implied rate of conversion from eddy kinetic energy to zonal mean kinetic energy is large and may be comparable to the fluxes of solar and internal energy.

Matched pairs of narrow-angle Voyager 1 frames (Smith et al., 1979), centered about a ten hour interval on February 26 and 27 1979, were selected for a preliminary analysis of motion of the observable cloud deck. These frames were obtained at the range of 7-8 x 10^6 km during the period when a 3 x 3 mosaic of narrow-angle images was needed to map the apparent disk. Accurate feature location information was determined by locating the bright planetary limb and hence the subspacecraft point in a wide-angle frame and then transferring this information to the simultaneously-shuttered narrow-angle frame. The camera pointing information was derived from trajectory and spacecraft motion measurements. Such shuttering was used only with the orange filter of the narrow-angle camera during this phase of the mission.

The ideal data set would consist of a pair of 3 x 3 mosaics separated by one Jovian rotation period ($9^h55^m29^s.711$, System III longitude) repeated around the planet to cover all longitudes. However, where data were missing, matched pairs from neighboring rotations were used, so the whole data set covers a 30 hour time interval. Longitudinal and latitudinal positions and velocity components u and v were obtained using the AMOS Interactive System (Yagi et al., 1978; Ingersoll et al., 1979) at the Image Processing Laboratory at JPL. Features down to 100 km in size were selected for tracking.

Figure 1 is a portion of the global map of measured velocity vectors. The location of each datum is designated by a dot, while the associated line points in the direction of the wind vector, its length indicating wind speed. Comparison of velocity vectors near 7° latitude with the magnitude of the mean zonal wind $\bar{u}$ given in Figure 2 allows scaling of the vectors on the map. As discussed in an earlier paper (Ingersoll et al., 1979) the relative vorticity gradient $d^2\bar{u}/dy^2$ exceeds the planetary vorticity gradient β at the latitudes of the westward jets, where y is the northward coordinate.

Figure 2 also shows the root mean square residual

$$\delta u = \left[\frac{1}{I} \sum_{i=1}^{I} (u_i - \bar{u})^2 \right]^{1/2} \qquad (1)$$

where I is the number of individual observations in a latitude bin (typically about 50), u_i is the ith observation, and $\bar{u}$ is the mean of u for the bin. Residuals δu and δv are typically 10-20ms^{-1}, and reflect both real eddy flows as well as measurement error. This measurement error arises from several sources: repeatability of individual measurements of u and v, and location and orientation of the spacecraft relative to the planet. For a time interval of one Jovian rotation at a range of 7.5 x 10^6 km, error of repeatability contributes ±2 ms^{-1}, and error in navigation also contributes ± 2 ms^{-1} (Voyager Optical Navigation Team, and JPL Guidance and Control Section, private communications, 1979). The combined measurement error σ for these frames is about ±3 ms^{-1}, equivalent to ±3 picture elements (pixels). This error strongly suggests that most of the residual δu is due to eddy flow.

The velocity correlation

$$\overline{u'v'} = \frac{1}{I} \sum_{i=1}^{I} (u_i-\bar{u}) \quad (v_i-\bar{v}) \qquad (2)$$

Paper number 9L1663.
0094-8276/80/009L-1663$01.00

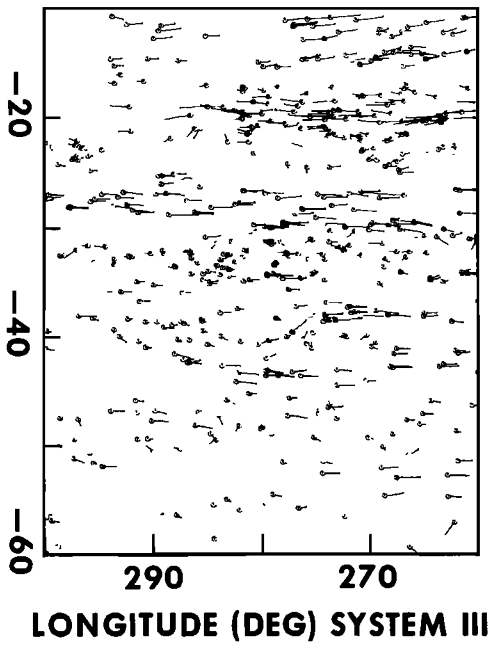

Fig. 1. A portion of the Voyager I "World Map" of velocity vectors. The data are derived from 70 frame pairs covering 3 Jovian rotation periods. Planetographic latitude and longitudes relative to System III are used. Velocity magnitudes may be obtained by comparing with Figure 2.

provides an estimate of the eddy momentum transport across latitude circles. The uncertainty in $\overline{u'v'}$ due to measurement error is $\sqrt{2}\,\sigma\,\delta u \sim 60\ m^2 s^{-2}$, which is comparable to $\overline{u'v'}$ itself. Figure 3 shows $\overline{u'v'}$ and $d\bar{u}/dy$ plotted as functions of latitude. Although the high-frequency scatter in $\overline{u'v'}$ is large, there is a positive correlation between the two curves that is discernable at both low and high latitudes. Figure 4 shows $\overline{u'v'}$ and $d\bar{u}/dy$ plotted against each other. The correlation coefficient r for 120 pairs of values (latitudes -60^{o} to 60^{o}) is 0.46, which is well above the 1% confidence value 0.23 for 118 degrees of freedom. The correlation between $\overline{u'v'}$ and $d\bar{u}/dy$ is positive and statistically significant, although only 1/5 ($\sim r^2$) of the variance of $\overline{u'v'}$ is associated with $d\bar{u}/dy$. The remaining fraction is largely measurement error, although eddy momentum transports $\overline{u'v'}$ uncorrelated with $d\bar{u}/dy$ may also contribute. The two straight lines are the least squares solutions of

$$\overline{u'v'} = A_1\, d\bar{u}/dy + B_1 \qquad (3)$$

and

$$d\bar{u}/dy = (1/A_2)\, \overline{u'v'} - (B_2/A_2) \qquad (4)$$

Table 1 lists the regression coefficients A_1 and A_2 as well as the linear correlation coefficients r for the entire data set (case 1) and for two subsets (cases 2 and 3). Case 1 is for all longitudes, and for latitudes -60° to +60°. The number of latitude bins N (degrees of freedom +2) is 120. Case 2 is for all longitudes, and latitudes 0° to 60°. Case 3 is for latitudes -60° to +60°, and latitudes 195° to 345°. Both cases 2 and 3 exclude the Red Spot and the three white ovals. Meridional velocity is larger around the edges of these vortices than at other places. However, the correlation between $\overline{u'v'}$ and $d\bar{u}/dy$ is significant for all cases, and is therefore a global feature. Because $\overline{u'v'}$ is the noisy variable, the linear relation between $\overline{u'v'}$ and $d\bar{u}/dy$ is better represented by equation (3) than equation (4). These equations are shown in Figure 4 for case 1.

We also looked for correlation between $\overline{u'v'}$ and $\bar{u}$, and between $\overline{u'v'}$ and $d^2\bar{u}/dy^2$. By symmetry, any significant correlation for these cases should be of opposite sign in the northern and southern hemispheres. In fact, the correlation for $\overline{u'v'}$ and $d^2\bar{u}/dy^2$ is not significant in either hemisphere (r = -0.16 and 0.03 in north and south respectively), and is only significant for $\overline{u'v'}$ and $\bar{u}$ in the northern hemisphere (r = 0.47 and 0.11

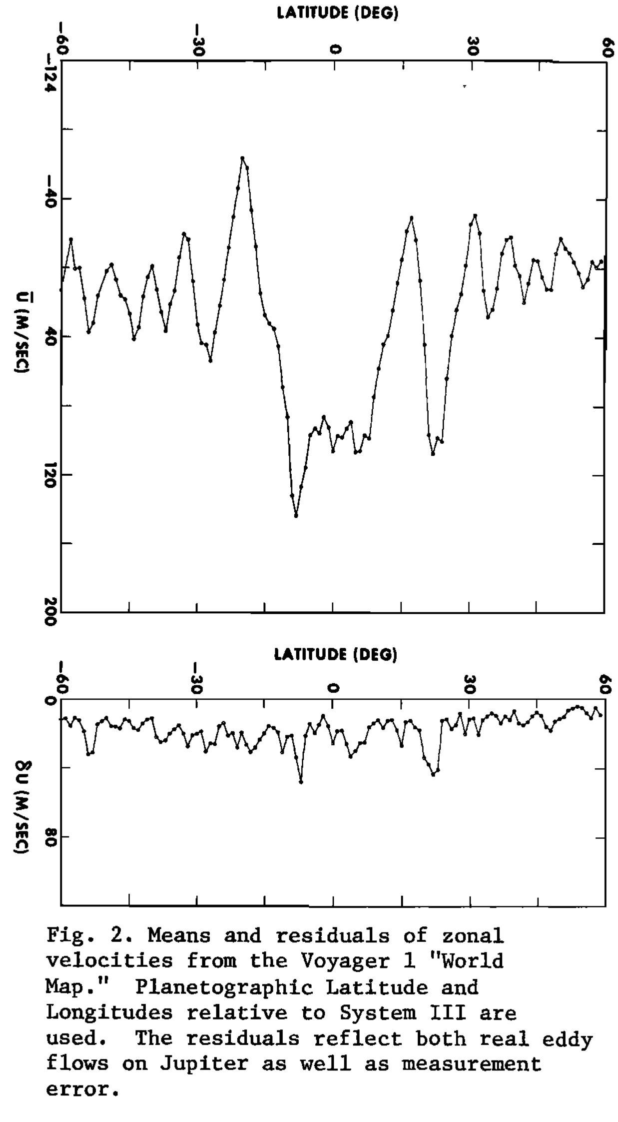

Fig. 2. Means and residuals of zonal velocities from the Voyager 1 "World Map." Planetographic Latitude and Longitudes relative to System III are used. The residuals reflect both real eddy flows on Jupiter as well as measurement error.

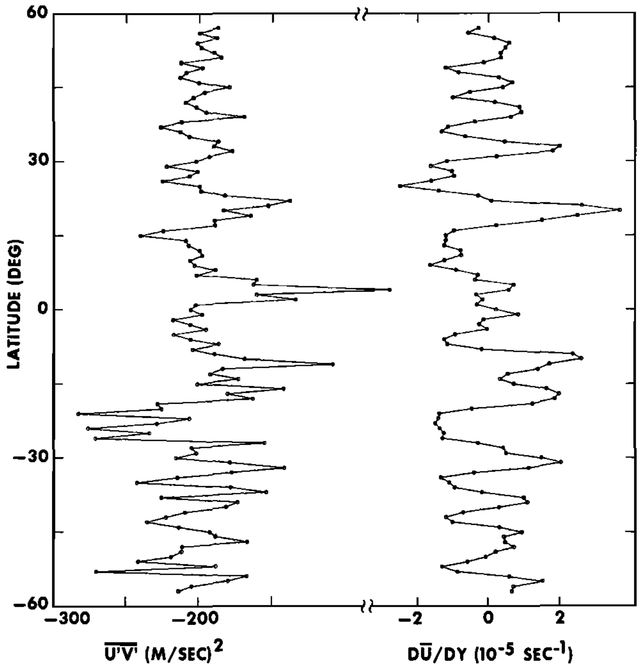

Fig. 3. Northward momentum flux $\overline{u'v'}$ and velocity gradient $d\bar{u}/dy$ as functions of latitude. Measurement error accounts for more than half of the variance in $\overline{u'v'}$. A statistically significant relation exists between $\overline{u'v'}$ and $d\bar{u}/dy$ at both low and high latitudes.

in north and south respectively). This positive correlation arises mainly at the northern hemisphere jets at 7° and 23° latitude which are the most difficult regions for identifying features on the entire planet. Tracking at higher spatial resolution over shorter time intervals should significantly reduce measurement error at these latitudes.

Because the correlation between $\overline{u'v'}$ and $d\bar{u}/dy$ is statistically significant, the product

$$\{K'\bar{K}\} = \frac{1}{N}\sum_{n=1}^{N} (d\bar{u}/dy)_n\,(\overline{u'v'})_n \qquad (5)$$

$$= 3.4 \pm 0.7\times10^{-4}\,m^2 s^{-3}$$

is significantly different from zero. The uncertainty quoted is a formal estimate, and does not allow for possible non-normal or systematic measurement errors. Nevertheless, it is interesting to speculate on the possible significance of a positive correlation between $\overline{u'v'}$ and $d\bar{u}/dy$. Such a correlation would indicate that the eddy momentum flux $\overline{u'v'}$ is on average toward latitudes where $\bar{u}$ is large. Equation (5) is therefore an estimate of the transfer rate $\{K'\bar{K}\}$ of eddy kinetic energy to zonal mean kinetic energy per unit mass at the level of observation (Holton, 1973). Multiplying by 10^4 kg m^{-2}, the mass per unit area in a layer 2.5 bar thick on Jupiter, we derive an estimate for the cloud zone $\{K'\bar{K}\} \sim 3$ W m^{-2}.

TABLE 1. Fit to $\overline{u'v'} = A\,d\bar{u}/dy + B$

Case	N	$A_1(10^6 m^2 s^{-1})$	$A_2(10^6 m^2 s^{-1})$	r
1	120	2.5±.5	12.4±2.3	.46
2	60	1.9±.5	11.1±3.1	.44
3	120	1.6±.4	14.2±3.8	.34

Further processing of Voyager data should refine our assessment of the statistical significance of equation (5). Uncertainty as to the mass per unit area will not be resolved by Voyager data. Nevertheless, 3 W m^{-2} is a large energy flux for Jupiter. The planetary average internal heat flux (Ingersoll et al., 1976) is 6 W m^{-2}, and the total infrared emission to space is 14 W m^{-2}. On the earth (Oort and Peixoto, 1974) $\{K'\bar{K}\}$ is about 0.3 W m^{-2}, and the infrared emission to space is about 240 W m^{-2}. Thus on both planets $\{K'\bar{K}\}$ is positive, but on Jupiter $\{K'\bar{K}\}$ is more than 10% of the total energy flux whereas on the earth $\{K'\bar{K}\}$ is only 0.1% of the total energy flux. The ratio of $[(\overline{u'v'})^2]^{1/2}$ to $\bar{u}^2$ for Jupiter is about 0.02, which is similar to such ratios for the earth.

The eddies would re-supply the zonal mean kinetic energy shown in Figure 2 [$\bar{u} \sim 50$ ms^{-1}] in 50 earth days, if the energy conversion rate of equation (5) were the only source. One cannot immediately conclude, however, that the eddies maintain the Jovian jets. Depending on the vertical distribution of the eddy momentum flux and the eddy heat flux, the eddies will drive mean meridional

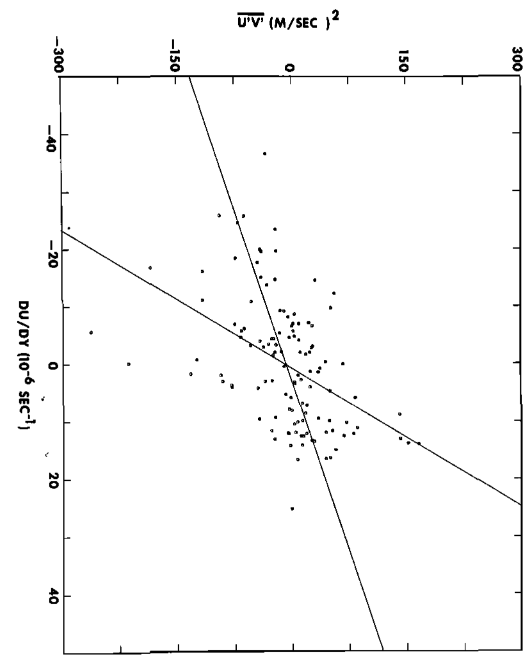

Fig. 4. Poleward momentum flux $\overline{u'v'}$ as a function of meridional shear in the zonal wind $d\bar{u}/dy$. The nearly horizontal line is equation (3); the nearly vertical line is equation (4).

circulations that also change the energy of the jets (Holton, 1973; Boyd, 1976; Andrews and McIntyre, 1976). Nevertheless, the measurements reported here do provide a constraint on models of the Jovian general circulation. The most comprehensive published model is that of Williams (1979), who finds the value of $\{K'\bar{K}\}$ oscillating between $\pm 10^{-3}\ m^2\ s^{-3}$ with a period of about 100-300 earth days. Such sign reversals are not excluded by our 30^h sample of Voyager 1 data. The magnitude of our result (5) is in general agreement with Williams' model.

These are preliminary results from work that is still in progress. Their worth rests on the correlation between $\overline{u'v'}$ and $d\bar{u}/dy$ being statistically significant. Measurement error is the major contributor to variation in $\overline{u'v'}$. Currently, Voyager 2 data, covering a period 4 months after Voyager 1, are being analyzed. Because of improvements in the observing sequence, studies at higher resolution in space and time are possible, and should lead to a substantial reduction in measurement error.

ACKNOWLEDGEMENTS

We would like to thank Glenn Garneau, Gary Yagi, Paul Jepsen, and Joel Mosher at the Image Processing Laboratory for their assistance with the interactive analysis of the Voyager images. This research is funded by NASA. GEH and J-PM acknowledge the financial assistance of the British Science Research Council, and J-PM the financial assistance of the Department of Physics and Astronomy of University College London.

References

Andrews, D. G., and M. E. McIntyre 1976: J. Atmos. Sci., 33, 2031.

Boyd, J. P. 1976: J. Atmos. Sci., 33, 2285.

Holton, J. R. 1973: An Introduction to Dynamic Meterology, Academic Press, New York.

Ingersoll, A. P., Beebe, R. F., Collins, S. A., Hunt, G. E., Mitchell, J. L., Müller, J.-P., Smith, B. A., Terrile, R. J., 1979: Nature, 280, 773.

Ingersoll, A. P., Munch, G., Neugebauer, G., Orton, G. S. 1976: Jupiter (ed. T. Gehrels) University of Arizona Press.

Jepsen, P. L., Mosher, J. A., Yagi, G. M., Avis, C. C., Lorre, J. L., Garneau, G. W. 1979: Voyager Image Processing at the Image Processing Laboratory presented at the B.I.S. Computers and Space Technology Conference entitled "Image Processing Techniques applied to Astronomy and Space Research, Nov. 15-16, 1979" Appleton Lab., Slough, England.

Oort, A. H., and J. P. Peixote, 1974: J. Geophys. Res., 79, 2705.

Smith, B. A., Soderblom, L. A., Johnson, T. V., Ingersoll, A. P., Collins, S. A., Shoemaker, E. M., Hunt, G. E., Masursky, H., Carr, M. H., Davies, M. E., Cook II, A. F., Boyce, J., Danielson, G. E., Owen, T., Sagan, C., Beebe, R. F., Veverka, J., Strom, R. G., McCauley, J. F., Morrison, D., Briggs, G. A., Suomi, V. E. 1979: Science, 204, 951.

Williams, G. P. 1979: J. Atmos. Sci., 36, 932.

Yagi, G., Lorre, J., Jepsen, P. 1978: "Proc. Conf. on Atmospheric Environment of Aerospace Systems and Applied Meteorology, Nov. 15-17, 1978" American Meteorological Society, Boston, Massachusetts, U.S.A.

(Received October 25, 1979; accepted November 27, 1979.)